# SOIL EROSION CHANGES IN PORTUGAL BETWEEN 1990 AND 2018

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Dissertation submitted in partial fulfilment of the requirements for the Degree of Mestre em Ciência e Sistemas de Informação Geográfica (Master in Geographical Information Systems and Science)

NOVA Information Management School

**NOVA Information Management School**

**Instituto Superior de Estatística e Gestão de Informação**

Universidade Nova de Lisboa

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Project Work presented as the partial requirement for obtaining a Master's degree in Geographic Information Systems and Science

**Advisor:** Professor Doutor Pedro da Costa Brito Cabral

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## DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

Lisbon, 27 of May of 2020

Susana Martins Marques

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Lisboa, 27 de Maio de 2020

Susana Martins Marques

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## NOTE

This work has been done in the form of a scientific paper, so that it can be submitted to a scientific journal.

## NOTA

Este trabalho foi realizado sob a forma de artigo científico, para que possa ser submetido numa revista científica.

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Soil erosion changes in Portugal between 1990 and 2018


# ABSTRACT

Soils provide important regulating ecosystem services and have crucial implications for human well-being and environmental conservation. However, soil degradation and particularly soil erosion jeopardize the maintenance and existence of these services. This study explores the spatio-temporal relationships of soil erosion to understand the distribution patterns of sediment retention services in mainland Portugal. Based on Corine Land Cover maps from 1990 to 2018, the InVEST Sediment Delivery Ratio (SDR) model was used to evaluate the influence of sediment dynamics for soil and water conservation. Spatial differences in the sediment retention levels were observed within the NUTS III boundaries, showing which areas are more vulnerable to soil erosion processes. Results indicated that the Region of Leiria, Douro and the coastal regions have decreased importantly sediment retention capacity over the years. However, in most of the territory (77.52%) changes in sediment retention were little or not important (i.e. less than 5%). The statistical validation of the model proved the consistency of the results, highlighting the usefulness of this methodology to analyse the state of soil erosion in the country. These findings can be relevant to support strategies for more efficient land use planning regarding soil erosion mitigation practices.

Soil erosion changes in Portugal between 1990 and 2018

## RESUMO

Os solos fornecem serviços de ecossistemas reguladores e têm implicações cruciais para o bem-estar humano e conservação do ambiente. No entanto, a degradação dos solos, particularmente a erosão do solo, coloca em risco a manutenção e a existência destes serviços. Este estudo pretende analisar a distribuição espaciotemporal da erosão do solo, compreendendo os padrões espaciais da retenção de sedimentos em Portugal continental. Suportado pela utilização dos mapas *Corine Land Cover* de 1990 a 2018, o modelo *Sediment Delivery Ratio (SDR)* do InVEST foi utilizado para avaliar a influencia das dinâmicas dos sedimentos para a conservação dos solos e água. Variações espaciais dos níveis de retenção de sedimentos dentro dos limites dos NUTS III foram observados, mostrando quais as áreas mais suscetíveis aos processos de erosão do solo. Os resultados indicam ainda, que na Região de Leiria, Douro e nas regiões costeiras a capacidade de retenção de sedimentos decresceu significativamente no decorrer dos anos. No entanto, na maioria do território (77,52%) as mudanças em retenção de sedimentos foram pouco ou nada importantes (isto é, menos de 5%). A validação estatística do modelo comprova a consistência dos resultados, destacando a utilidade desta metodologia para a análise do estado da erosão do solo no país. Estas descobertas podem ser relevantes para apoiar estratégias para um ordenamento de território mais eficiente, relativamente às práticas de mitigação da erosão do solo.

## KEYWORDS

Ecosystem Services,

Spatial Modelling,

Soil Erosion,

Sediment Retention,

InVEST model

## PALAVRAS-CHAVE

Serviços de Ecossistemas

Modelação Espacial

Erosão do Solo

Retenção de Sedimentos

Modelo InVEST

## ACRONYMS

**ASTER -** Advanced Spaceborne Thermal Emission and Reflection Radiometer

**CLC -** Corinne Land Cover

**DEM -** Digital Elevation Model

**DGT -** Directorate-General for Territory (*Direção Geral do Território*)

**EEA -** European Environmental Agency

**ESA -** European Space Agency

**ESDAC -** European Soil Data Centre

**ESRI -** Environmental Systems Research Institute

**ETRS_1989_TM06** - European Terrestrial Reference System_1989_Tranverse Mercator06

**GloREDa -** Global Rainfall Erosivity Database

**IDW -** Inverse Distance Weighting

**JRC -** Joint Research Centre

**LUCAS -** Land Use and Coverage Area frame Survey

**MMU -** Minimum Mapping Unit

**NASA -** National Aeronautics and Space Administration

**NUTS III -** Nomenclature of Territorial Units for Statistics level 3

**REDES -** Rainfall Erosivity Database at European Scale

**RUSLE -** Revised Universal Soil Loss Equation

**SDR -** Sediment Delivery Ratio

**SNIG -** Portuguese Geographical Information National System (*Sistema Nacional de Informação Geográfica*)

**TFA -** Threshold Flow Accumulation

**USGS -** United States Geological Survey

**USLE -** Universal Soil Loss Equation

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# 1. INTRODUCTION

Soil erosion is a natural process responsible for shaping the physical landscape through the distribution of weathered materials produced by geomorphic processes (Panagos, et al., 2014b). However, when soil erosion occurs in an accelerated rate due to anthropogenic activities, wind, or water, deterioration or loss of the natural soil functions are likely to ensue (Panagos, et al., 2014b).

Soils perform a range of key functions, including the production of food, the storage of organic matter, water and nutrients, the provision of a habitat for a huge variety of organisms and preserving a record of past human activity, any degradation in the quality of the soil resource through erosion can have an impact on the ability of soils to perform this range of functions (Webster, 2005). Preserving soil resources through erosion prevention is a safeguard procedure to protect the ecological environment and the ability of soils to contribute to ecosystem functioning (Wu et al., 2020). Soil loss by water is closely related to rainfall partly through the detaching power of raindrops striking the soil surface, and, partly, through the contribution of rain to runoff (Webster, 2005). Soil erosion by water has become one of the greatest global threats to the environment (Navarro-Hevia, et al., 2016). As a consequence, soil condition, water quality, species habitats and the provision of ecosystem services are negatively affected, so it has become important to quantify the impacts of soil erosion by water and to develop effective measures for soil and water conservation (Teng et al., 2018).

Due to the difficulty to measure soil erosion at large geographical scales, soil erosion models are suitable tools for regional and national estimations (Panagos, et al., 2014a). However, the high heterogeneity of soil erosion causal factors combined with often poor data availability is an obstacle for the application of complex soil erosion (Panagos, et al., 2014a).

Using a combination of remote sensing, Geographic Information Systems (GIS) modelling and census data, several studies have demonstrated the effects of land use and land cover on soil erosion worldwide (Bathurst et al., 2007; Borrelli et al., 2017; Burylo et al., 2012; Wu et al., 2020; Zhang et al., 2015). At European level, Morgan et al. (1998) explored the use of the European Soil Erosion Model (EUROSEM) to simulate erosion processes, explicitly for rill and inter-rill flow. More recently, the RUSLE2015 model estimated soil loss at 100 m resolution for Europe (Panagos et al., 2015c). A recent study conducted by Aneseyee et al. (2020) analysed soil loss and sediment exportation at the Winike watershed in Ethiopia, concluding that land use changes greatly affects the amount of soil loss in cultivated areas. Another recent study by Duan et al. (2020) evaluated the soil erosion at a regional scale at Yunnan Province, China, using the Chinese Soil Loss Equation (CSLE) which allowed a more accurate soil erosion map for that province.

Particularly for Portugal, some studies have been carried out for modelling soil erosion at local scales (da Silva et al., 2009; Martins et al., 2019; Nunes et al., 2010). For example, da Silva et al. (2009) studied the nutrient retention by trade-offs between sediments and vegetation types in Ria de Aveiro lagoon (central Portugal). Nunes et al. (2010) explored the effects of land abandonment on soil erosion and land degradation in the River Côa Valley (north-eastern Portugal). Recently, Martins et al. (2019) investigated the influences of gully erosion in steep regions in the northern territory of Portugal.

Albeit these studies have been made in different regions of Portugal, a deeper and validated study is yet to be carried to explain the effect of sediment retention on soil erosion in the entire territory. To contribute to filling this gap, the present study explores the spatio-temporal distribution of soil erosion by understanding the spatial patterns of the sediment retention capacity in mainland Portugal, based on Land Cover changes between 1990 and 2018. Specifically, this study aims to: (i) estimate the soil loss at a pixel scale, and to (ii) estimate sediment retention variations at NUTS III level.

The study uses the InVEST Sediment Delivery Ratio (SDR) model to determine the behaviour of sediment retention in Portugal's mainland. The results provide a unique perspective on soil erosion and sediment retention for Portugal, contributing with useful information to design a landscape effective planning for soil and water conservation.

# 2. MATERIALS AND METHODS

## 2.1. Study Area

This study focuses on mainland Portugal (Figure 1). Portugal, is a country in southern Europe, occupying a total area of 92,212 km2, whereas the mainland has a total area of 89,102.14 km2, with 23 statistical boundaries defined as NUTS III (Eurostat, 2009a; Governo de Portugal, 2018). The mainland is located on the southwest of the Iberian Peninsula, bordering with Spain to the north and east, and with the Atlantic Ocean to the west and south.  The North and Center regions of the Portuguese territory present a very mountainous terrain. The climate is predominantly temperate throughout the Portuguese mainland (IPMA, 2011).

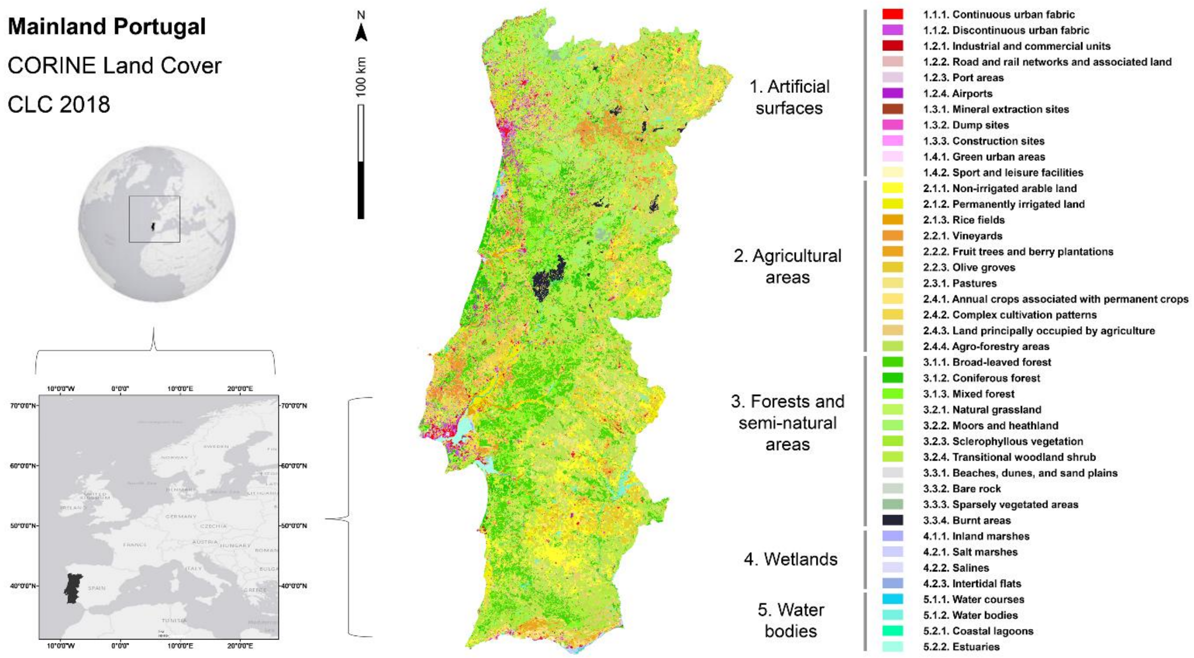


*Figure 1. Study area - National map, showing all land use land cover, from Corine Land Cover of 2018.*

## 2.2. Sediment Delivery Ratio Model

The current soil erosion by water was estimated using InVEST 3.6.0 software, from Natural Capital Project (Sharp et al., 2018). The InVEST models are “ready-to-use” models, i.e. after the user collect and pre-process the input required data, the model runs in a simple interface and delivers the expected output The InVEST models are “ready-to-use” spatially explicit models, i.e. after the user collect and pre-process the required input data, the model runs in a simple interface and delivers the expected outputs (Sharp et al., 2018). The SDR model is based on the concept of hydrological connectivity requiring a minimal number of parameters (Sharp et al., 2018). The applied model uses the RUSLE[1] method, where the factors are derived from different maps provided from different sources, in order to determine the annual soil loss (Sharp et al., 2018). RUSLE is an extension of the original USLE[2] with improvements in determining the factors controlling erosion (Renard et al., 1997; Wischmeier and Smith, 1978). This is an empirical model commonly used to estimate soil loss potential by water from hill-slopes across large areas of land. It estimates the annual soil loss that is due to erosion using a factor-based approach with rainfall, soil erodibility, slope length, slope steepness and cover management and conservation practices as inputs (Teng et al., 2016).

Both the USLE and the RUSLE equations are written as follows (Winchell et al., 2008) (1):

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

where A is the soil loss (ton $ha^{-1}$ $y^{-1}$); R is the rainfall erosivity factor (MJ mm $ha^{-1}$ $h^{-1}$ $y^{-1}$); K is the soil erodibility factor (ton ha h [ha MJ mm]$^{-1}$); L is the slope length factor; S is the slope steepness factor; C is the cover management factor; and P is the supporting practice factor, the L and S terms of the equation are often lumped together as "LS" and referred to as the topographic factor (Winchell et al., 2008).

## 2.3. Data

Table 1 shows the data used as input for the SDR model in InVEST.

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[1] *Revised Universal Soil Loss Equation*
[2] *Universal Soil Loss Equation*

| Data | Source |
|---|---|
| Digital Elevation Model (DEM) | (USGS, 2008) |
| Rainfall Erosivity Index (R) | (JRC-ESDAC, 2017) |
| Soil Erodibility (K) | (JRC-ESDAC, 2015) |
| Land Use/Land Cover | (DGT, 2013)(Copernicus, 2015) |
| P[a] and C[b] coefficients | (Panagos, *et al.*, 2015a, 2015b) |
| Watersheds | (SNIG, 2013) |
| Biophysical table | Created by analyst |

a Support practice factor

b Cover-management factor

*Table 1. Data sources for the data used as inputs for the SDR InVEST model.*

Relevant parameters used in SDR include the definition of the threshold flow accumulation (TFA) value which represents the number of upstream cells that must flow into a cell before it is considered part of a stream; two calibration parameters, $k_b$ and $IC_0$, which determine the degree of connection from patches of land to the stream and percentage of soil loss that actually reaches the stream; and the $SDR_{max}$, which is the maximum SDR that a pixel can reach, in function of the soil texture. The default values were used, as indicated in the InVEST user guide for this model (Sharp et al., 2018).

### *2.3.1. Digital elevation model (DEM)*

The 30 m digital elevation model (DEM) was retrieved from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (NASA, 2009; USGS, 2008).

### *2.3.2. Rainfall Erosivity Index (R)*

The rainfall erosivity index is an indicator of the ability of water to detach and transport soil particles; thus, erosion is sensitive to the intensity and duration of rainfall (Teng et al., 2016). This index was provided by GloREDa, the Global Rainfall Erosivity Database, from the Joint Research Centre - European Soil Data Centre (ESDAC) (JRC-ESDAC, 2017). GloREDa contains erosivity values estimated as R-factors from 3,625 stations distributed in 63 countries worldwide. This is the result of an extensive data collection of high temporal resolution rainfall data from the maximum possible number of countries in order to have a representative sample across different climatic and geographic gradient. It has three components: a) the Rainfall Erosivity Database at European Scale (REDES) (EEA, 2016); b) 1,865 stations from 23 countries outside Europe; and c) 85 stations collected from a literature review. As such, it is the most comprehensive global database including the largest possible number of stations with high temporal resolution rainfall data (Panagos et al., 2017).

#### *2.3.3. Soil Erodibility (K)*

The soil erodibility factor (K-factor) is a lumped parameter that represents an integrated average annual value of the soil profile reaction to the processes of soil detachment and transport by raindrop impact and surface flow (Renard et al., 1997). Consequently, K-factor is best obtained from direct measurements on natural plots (Panagos, et al., 2012). However, this is a difficult task on a national or continental scale. To overcome this problem, measured K factor values have been related to soil properties. Panagos et al., (2012) estimated soil erodibility, at European level, based on attributes (texture, organic carbon) which were available from the Land Use/Cover Area frame Survey (LUCAS) (Eurostat, 2009b) topsoil data, using the original nomograph of Wischmeier, et al., (1971). Inverse distance weighting (IDW) was used to interpolate erodibility to a map with a grid-cell resolution of 10 km (Panagos, et al., 2014a).

#### *2.3.4. Land Use/Land Cover*

The land use/land cover products used in this project, were the Corine Land Cover (CLC) maps from European Environmental Agency (EEA). CLC is a thematic land use/land cover cartography, available for the years 1990, 2000, 2006, 2012, and 2018, produced by the Directorate-General for the Territorial Development Portugal (DGT) for a project coordinated by the EEA. It consists of an inventory of land cover in 44 classes, it uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena (DGT, 2013).

#### *2.3.5. Calibration coefficients C and P*

The cover-management factor (C-factor) is used within both the USLE and the RUSLE to reflect the effect of cropping and management practices on erosion rates (Panagos et al., 2015a). That is the mostly used factor to compare the relative impacts of management options on conservation plans, indicating how the conservation plan will affect the average annual soil loss and how that potential soil loss will be distributed in time during construction activities, crop rotations, or other management schemes (Renard et al., 1997). The study made by Panagos, , et al. (2015a), where the authors made an estimation for C-factor values at a European level, was the starting point to estimate the C-factor values, for the different land use/cover of the present study.

The support practices factor (P-factor) accounts for control practices that reduce the erosion potential of runoff by their influence on drainage patterns, runoff concentration, runoff velocity and hydraulic forces exerted by the runoff on the soil surface. It is an expression of the overall effects of supporting conservation practices – such as contour farming, strip cropping, terracing, and subsurface drainage – on soil loss at a particular site, as those practices principally affect water erosion by modifying the flow pattern, grade, or direction of surface runoff and by reducing the volume and rate of runoff (Renard et al., 1997). The value of P-factor decreases by adopting these supporting conservation practices as they reduce runoff volume and velocity and encourage the deposition of sediment on the hill slope surface. The lower the P-factor value, the better the practice is for controlling soil erosion (Panagos, et al., 2015b). Considering Panagos et al., (2015b) the P-factor used for Portugal is 0.9178, for every CLC class.

Both, C-factor and P-factor, are floating points, with values between 0 and 1 (Sharp et al., 2018).

### *2.3.6. Watersheds*

The watersheds polygons were provided by the National Spatial Data Infrastructure (SNIG). This is the national infrastructure that allows the recording and the search of geographic data and services by both public and private entities. The original dataset is in vector format, as shapefile.

### *2.3.7. Biophysical table*

The biophysical table (Table 2) was constructed using the CLC classes, and the C and P factors, as mentioned in a previous section, by reviewing studies from the literature (Panagos et al. 2015a; Panagos et al. 2015b), and by adapting some values (for water bodies, for example) from the biophysical table from the Natural Capital Project sample data. In the biophysical table shown in table 2, the C-factor is represented by the usle-c field, and the P-factor is represented by the usle-p field. The lucode field, represents the CLC-code for each class.

| Biophysical Table | | | |
|---|---|---|---|
| lucode | label | usle-c | usle-p |
| 111 | Continuous urban fabric | 0.1 | 0.9178 |
| 112 | Discontinuous urban fabric | 0.06 | 0.9178 |
| 121 | Industrial or commercial units | 1 | 0.9178 |
| 122 | Road and rail networks and associated land | 1 | 0.9178 |
| 123 | Port areas | 0.25 | 0.9178 |
| 124 | Airports | 0.25 | 0.9178 |
| 131 | Mineral extraction sites | 1 | 0.9178 |
| 132 | Dump sites | 0.9 | 0.9178 |
| 133 | Construction sites | 0.2 | 0.9178 |
| 141 | Green urban areas | 0.003 | 0.9178 |
| 142 | Sport and leisure facilities | 0.06 | 0.9178 |
| 211 | Non-irrigated arable land | 0.46 | 0.9178 |
| 212 | Permanently irrigated land | 0.36 | 0.9178 |
| 213 | Rice fields | 0.15 | 0.9178 |
| 221 | Vineyards | 0.4 | 0.9178 |
| 222 | Fruit trees and berry plantations | 0.3 | 0.9178 |
| 223 | Olive groves | 0.3 | 0.9178 |
| 231 | Pastures | 0.15 | 0.9178 |
| 241 | Annual crops associated with permanent crops | 0.35 | 0.9178 |
| 242 | Complex cultivation patterns | 0.2 | 0.9178 |
| 243 | Land principally occupied by agriculture, with significant areas of natural vegetation | 0.2 | 0.9178 |
| 244 | Agro-forestry areas | 0.13 | 0.9178 |
| 311 | Broad-leaved forest | 0.003 | 0.9178 |
| 312 | Coniferous forest | 0.003 | 0.9178 |
| 313 | Mixed forest | 0.003 | 0.9178 |
| 321 | Natural grasslands | 0.08 | 0.9178 |
| 322 | Moors and heathland | 0.1 | 0.9178 |

| Biophysical Table (continued) | | | |
|---|---|---|---|
| lucode | label | usle-c | usle-p |
| 323 | Sclerophyllous vegetation | 0.1 | 0.9178 |
| 324 | Transitional woodland-shrub | 0.05 | 0.9178 |
| 331 | Beaches, dunes, sands | 0 | 0.9178 |
| 332 | Bare rocks | 0 | 0.9178 |
| 333 | Sparsely vegetated areas | 0.45 | 0.9178 |
| 334 | Burnt areas | 0.55 | 0.9178 |
| 411 | Inland marshes | 0 | 0.9178 |
| 421 | Salt marshes | 0 | 0.9178 |
| 422 | Salines | 0 | 0.9178 |
| 423 | Intertidal flats | 0 | 0.9178 |
| 511 | Water courses | 0 | 0.9178 |
| 512 | Water bodies | 0 | 0.9178 |
| 521 | Coastal lagoons | 0 | 0.9178 |
| 522 | Estuaries | 0 | 0.9178 |
| 523 | Sea and ocean | 0 | 0.9178 |

*Table 2. Biophysical table used in the SDR model, where 'lucode' is the CLC code for each land use class, 'label' is the description of the class, and 'usle-c' and 'usle-p' are the C and P factors, respectively*

### 2.3.8. Threshold flow accumulation, $k_b$, $IC_0$ and $SDR_{max}$

The TFA represents the number of upstream cells that must flow into a cell before it is considered part of a stream, which is used to classify streams from the DEM. $IC_0$ and $k_b$ are two calibration parameters that determine the shape of the relationship between hydrologic connectivity and the sediment delivery ratio. The $SDR_{max}$ is the maximum SDR that a pixel can reach. The values for the SDR model are presented in table 3. As mentioned above, the used values in this study are the default values in the InVEST user guide (Sharp et al., 2018).

| Parameters | Value |
|---|---|
| Threshold flow accumulation | 1000 |
| kb | 2 |
| IC0 | 0.5 |
| $SDR_{max}$ | 0.8 |

*Table 3. Values used for the threshold flow accumulation, kb, IC0 and SDRmax parameters.*

## 2.4. Methodology

The SDR model, follows the workflow presented in Figure 2. This is a simple methodology, that is explained in the software user's guide (Sharp et al., 2018).

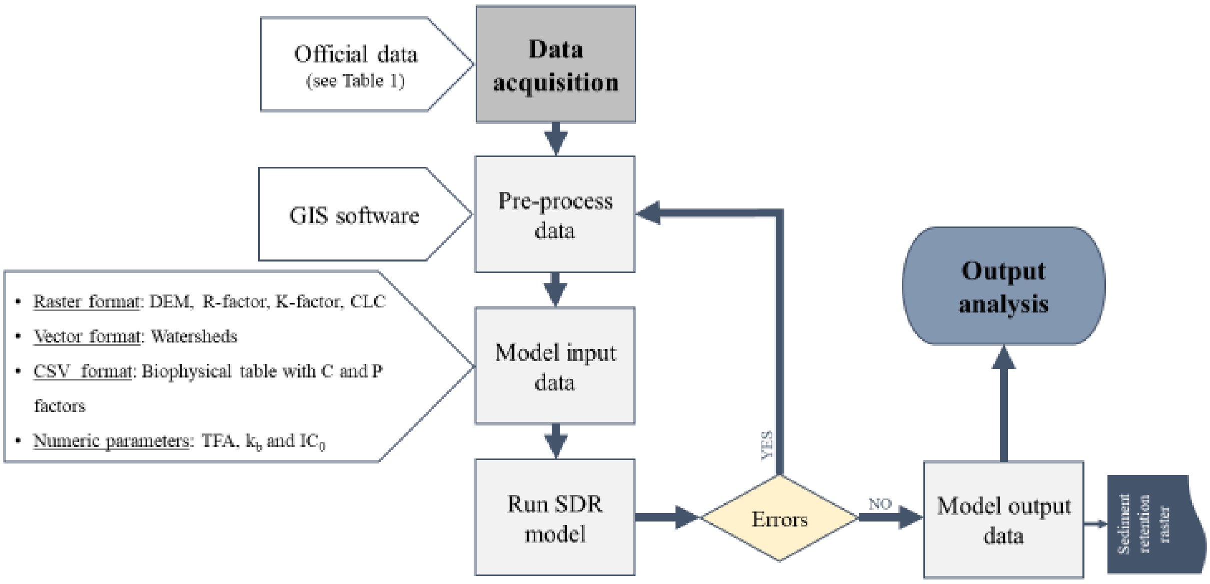


*Figure 2. SDR model workflow.*

The model has a simple interface, that runs with the data already mentioned in the previous sections which needs to be pre-processed with a GIS software. The software used to pre-process all the geographical data was the ArcMap 10.7.1 for desktop (ESRI, 2017). All the input data had the ETRS_1989_TM06 coordinate system. The model's output data was then analysed with the same GIS software.

## 2.5. Model validation

To validate the SDR model, and its ability to assess soil erosion, we carried out a mean statistical test (t-test) to compare our results with the publicly available Soil Erosion by Water (RUSLE2015) Dataset, provided by European Soil Data Centre (ESDAC)[1]. The RUSLE2015 dataset uses a modified version of the Revised Universal Soil Loss Equation (RUSLE) model, which delivers improved estimates due to higher resolution (100 m) and validated input layers (rainfall erosivity, soil erodibility, topography, cover-management

[1] *European Commission, Joint Research Centre, esdac.jrc.ec.europa.eu*

and support practices) from the year 2010 (the latest year for which most of the input factors are estimated) (Panagos, et al., 2015c). This dataset refers to the 28 Member States of the European Union, making it simple to extract the soil loss information for Portugal.

# 3. RESULTS AND DISCUSSION

The SDR model was computed for five time moments, corresponding to the years of the available CLC maps: 1990, 2000, 2006, 2012, and 2018.

## 3.1. Sediment retention

Along the 28 years evaluated, the sediment retention stays fairly the same, ranging from 7.4 ton/ha in 1990 to 7.3 ton/ha in 2018, representing a decrease of 0.2%. The values for 2000, 2006 and 2012 were very similar, i.e., 7.4, 7.3 and 7.4 ton/ha, respectively.

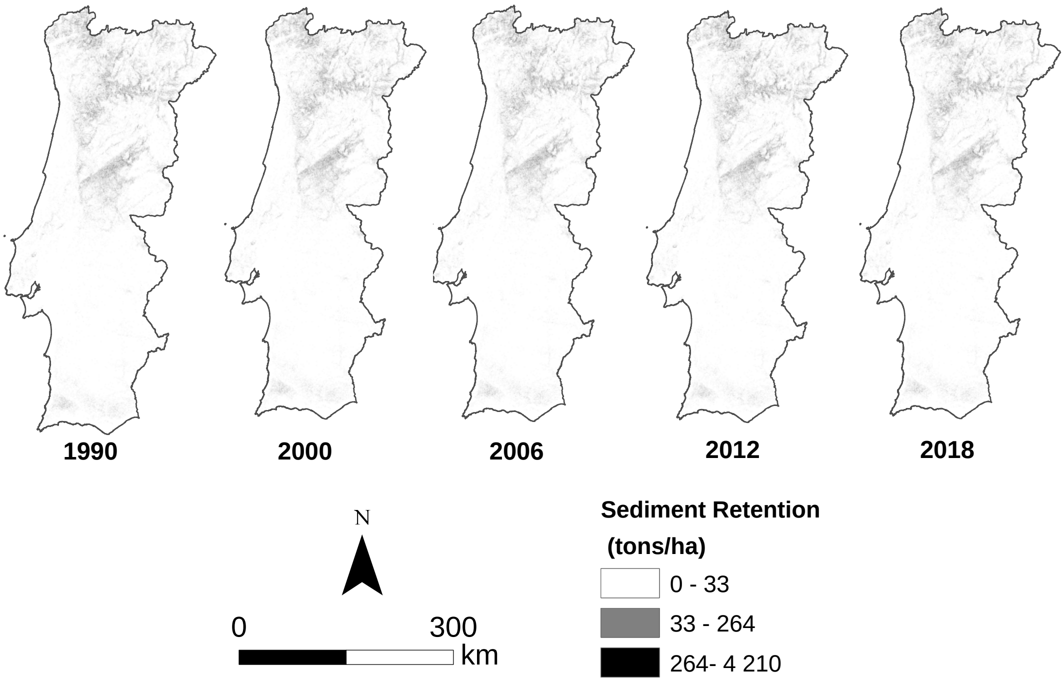


*Figure 3. Sediment retention for 1990, 2000, 2006, 2012 and 2018 - SDR outputs.*

The SDR outputs (Figure 3) for each of the years do not provide much information by themselves. Therefore, to better understand the outputs obtained, the raster calculator in ArcToolbox was used to calculate the percentage of gain/loss of sediment retention between 1990 and 2018. The expression (2) used to calculate the sediment retention change, presented in Figure 3, between 1990 and 2018 was:

$$Sediment\ Retention\ Change\ (\%) = \frac{(SR_{2018} - SR_{1990})}{SR_{1990}} \times 100 \tag{2}$$

Where $SR_{1990}$ and $SR_{2018}$, are the raster outputs from the SDR model, from 1990 and 2018, respectively.

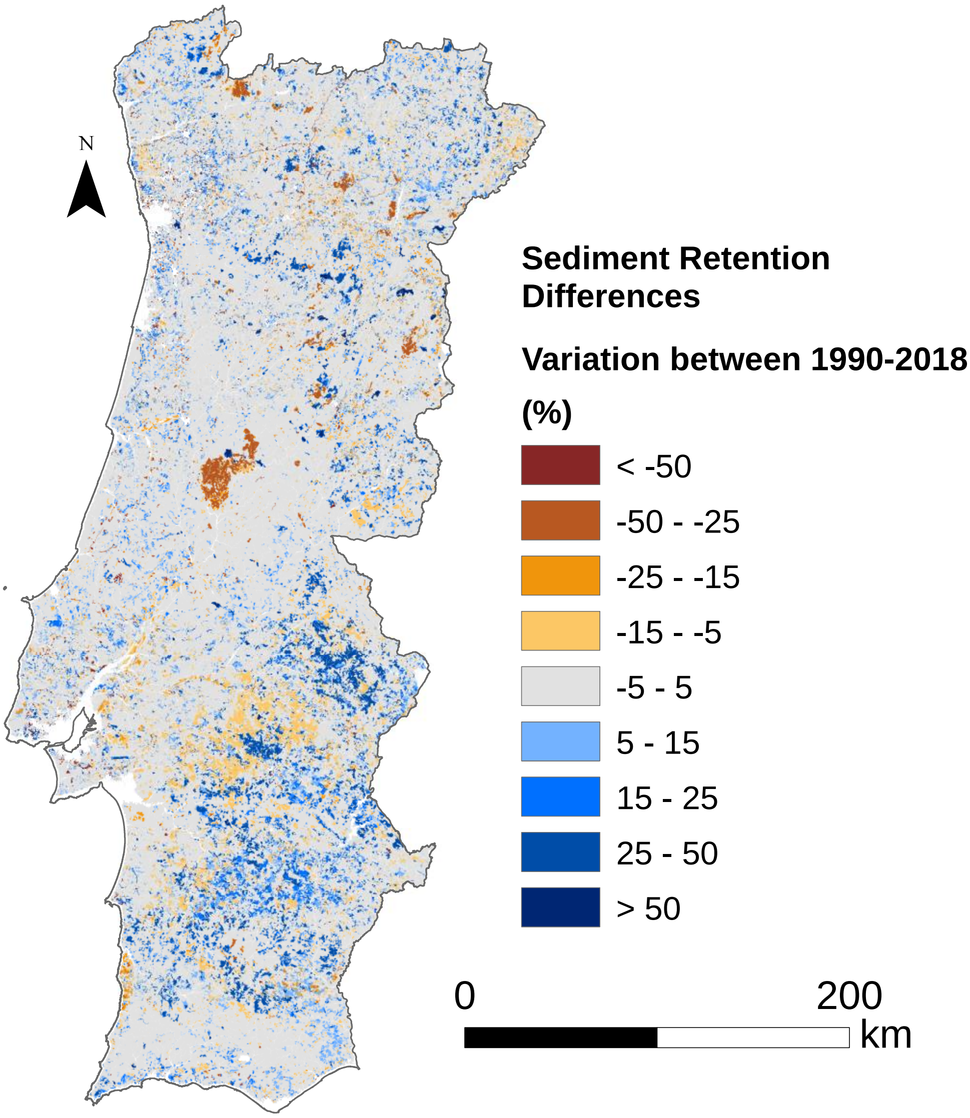


*Figure 4. Sediment retention difference, between 1990 and 2018 using raster calculator*

In Figure 4, it is possible to see that the difference of sediment retention throughout the territory is, mainly, between -5 and 5%, indicating that the territory did not suffer great variation in terms of the capacity to retain sediments. A further analysis of the calculated raster shows that the percentage of variation of each class in the territory (Table 4). The results reveal that the sediment retention capacity is relatively the same throughout the Portuguese territory (77.52%) in the 28 year's timeframe.

| Class | Area per Class (km$^2$) | Territory variation (%) |
|---|---|---|
| < -50 | 1314.95 | 1.21 |
| -25 - -15 | 1088.94 | 1.33 |
| -15 - -5 | 3972.48 | 4.85 |
| -5 - 5 | 63449.31 | 77.52 |
| 5 - 15 | 5557.27 | 6.79 |
| 15 - 25 | 2501.10 | 3.06 |
| 25 - 50 | 3726.13 | 4.55 |
| > 50 | 242.10 | 0.30 |
| **Total** | 81852.28 | 100 |

*Table 4. Sediment retention change, from 1990 to 2018, percentage of territorial variation.*

## 3.2. Statistical analysis of SDR outputs

To understand which regions present a higher loss or gain in the capacity to retain sediments, a statistical analysis was applied to the map in Figure 4 using zonal statistics tool from ArcGIS ArcToolbox. The map of Figure 5 shows the mean values differences (%) between 1990 and 2018 obtained per NUTS III after the classification in natural breaks[1].

The regions represented in grey in the map of Figure 5 have fairly the same capacity of sediment retention throughout the years. Douro and the coastal regions are the ones that have a greater loss in sediment retention (peach colour), especially the region of Leiria (dark red colour), which was greatly affected by the 2017 forest fires. The Alentejo regions increased their capacity to retain sediments during the period of study (blue colour).

In the chart of Figure 5 it is possible to observe sediment retention (ton/ha) by NUTS III for each year. *Alto Minho* is the region with better capacity to retain more sediments while *Lezíria do Tejo* is the region with the lowest capacity.

[1] *Jenks natural breaks classification, based on natural grouping of similar values, maximizing the differences between classes.*

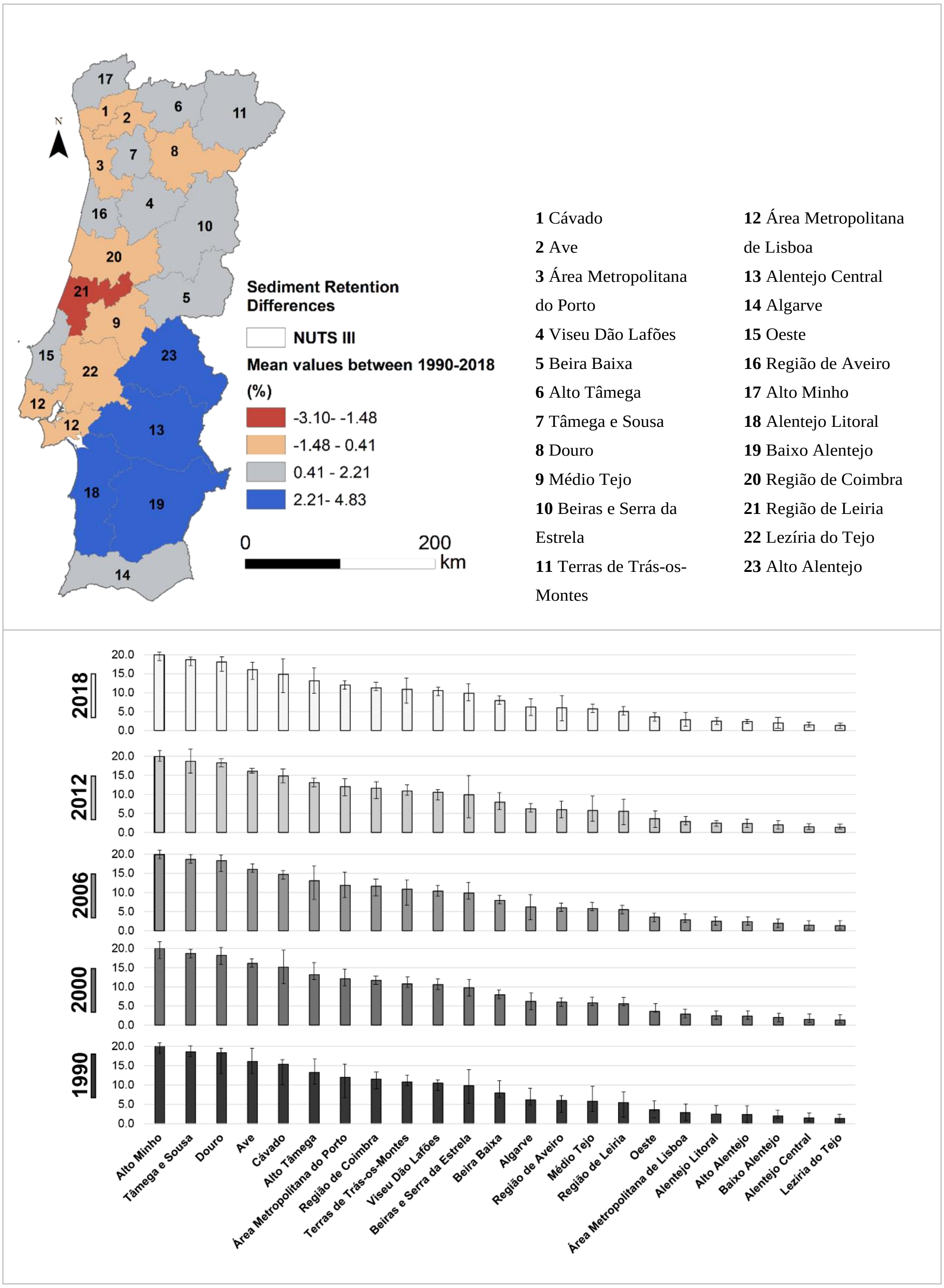


*Figure 5. Sediment retention SDR output analysis. Top: map with zonal statistics analysis, per NUTS III region, for 1990 to 2018 timeline (classes obtained by natural breaks); Bottom: chart with statistics analysis, per NUTS III region, from NUTS III with higher mean values to lowest.*

If wildfires directly influenced sediment retention losses, other causes that may justify the differences in sediment retention from 1990 to 2018 include changes in land use, especially for agriculture and urban growth. Another potential important explanation for the differences found in sediment retention is drought. According to the technical report of the European Environmental Agency (EEA, 2010), 2004/05 was the year that has suffered one of the worst droughts ever recorded in the Iberian Peninsula, with only half of the average precipitation, causing the considerable decrease of the rivers flow. In 2003 and 2005, extreme fires followed by drought deeply affected the amount of sediment retention.

### 3.3. Model validation

For the model validation, the model output *usle* was used. This output represents the total potential soil loss by water per pixel in the original land cover calculated from the USLE equation (Sharp et al., 2018). A mean value was obtained for each of the 23 NUTS III regions for the year 2018 (Table 5). Then, these values were compared with the ones using the ESDAC RUSLE2015 through a t-test. The null hypothesis was not rejected, i.e. the observed difference of the sample means (3.97 - 2.91) is not enough to say that the means of *usle* and RUSLE2015 differ significantly. Thus, the model outputs are coherent with the ESDAC official data.

| NUTS III | USLE (2018) | ESDAC (reference) |
|---|---|---|
| Cávado | 7.281 | 6.090 |
| Ave | 6.593 | 5.455 |
| Área Metropolitana do Porto | 4.351 | 4.455 |
| Viseu Dão Lafões | 3.593 | 3.256 |
| Beira Baixa | 2.186 | 0.980 |
| Alto Tâmega | 5.775 | 3.474 |
| Tâmega e Sousa | 8.742 | 7.643 |
| Douro | 11.859 | 6.039 |
| Médio Tejo | 1.996 | 0.866 |
| Beiras e Serra da Estrela | 4.165 | 2.761 |
| Terras de Trás-os-Montes | 4.910 | 2.716 |
| Área Metropolitana de Lisboa | 1.847 | 1.773 |
| Alentejo Central | 1.149 | 1.067 |
| Algarve | 2.206 | 1.871 |
| Oeste | 3.231 | 3.226 |
| Região de Aveiro | 1.476 | 1.320 |

| NUTS III (cont.) | USLE (2018) (cont.) | ESDAC (reference) (cont.) |
|---|---|---|
| Alto Minho | 7.975 | 7.703 |
| Alentejo Litoral | 0.837 | 0.729 |
| Baixo Alentejo | 1.468 | 1.556 |
| Região de Coimbra | 3.689 | 1.312 |
| Região de Leiria | 3.984 | 1.013 |
| Lezíria do Tejo | 0.723 | 0.758 |
| Alto Alentejo | 1.305 | 1.052 |
| **Total (ton/ha)** | 67.117 | 91.340 |
| **Mean (ton/ha)** | 3.971 | 2.918 |

*Table 5. Soil loss average value (ton/ha) for each NUTS III region in mainland Portugal, according to model output (USLE) for year 2018. Source: ESDAC dataset*

## 3.4. Limitations

According to Sharp et al. (2018), the SDR model presents some limitations. The USLE (Renard et al., 1997) usage is very common, but this equation is limited in scope, it only represents rill/inter-rill erosion processes. Mass erosion processes such as, landslides, significantly impact to determine the amount of soil erosion in some areas. Nonetheless, those processes are not represented in this model. The SDR model is also very sensitive to $k_b$ and $IC_0$ parameters, which are not physically based.

Another limitation is that the model produces 'NoData' pixels in the stream network. The reason behind is justified by the lack of in-stream processing. As it moves sediment down the slope, it stops calculations when the sediment reaches the stream, so in the estuary areas, where we have great water bodies, it can occur some pixel errors in the water/land border. Besides, the SDR model is highly sensitivity to most of the input data (due to its simplicity and the low number of parameters), which took a fair amount of time to process and adjust to the model. Additionally, the time it took to run process the model, due to the heavy data inputs, was also a constrain.

## 4. CONCLUSION

This study assessed the changes in sediment retention in mainland Portugal between 1990 and 2018. We quantified the effects of land use changes on the Portuguese hydrological basins and its impacts on soil erosion. Results show the different dynamics in sediment retention over the years at NUTS III level. The greater losses in sediment retention were observed in the Douro and coastal regions and, especially in the Region of Leiria. The model validation confirms that the outputs obtained are consistent with the ESDAC official data, demonstrating that the InVEST SDR model is an appropriate tool for estimating soil loss potential by water at regional/national levels. Besides contributing with new information about sediment retention for Portugal in a 28-year frame, this study also provides a straight-forward validation methodology of the results using credible reference datasets. This methodology can be easily replicated for other study areas. Future developments of this work should include a sensitivity analysis with advanced computational algorithms such as neural networks, to determine how the model is affected when the values of the Borselli parameters kb, the connectivity index IC0, and the TFA values are calibrated to achieve the model's optimal performance. Other future improvement should include the determination of the actual amount of sediments in each pixel to acknowledge where and how much soil gets deposited as it moves downhill towards a stream, or to quantify the erosion in the territory without converting the LULC classes as bare soil.

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